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Determination of soil water evaporation and transpiration from energy balance and stem flow measurements*

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ABSTRACT

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Frequent measurements of soil water evaporation (E) and transpiration (T) are needed to quantify energy and water balances of sparse crops. Field experiments were conducted in Lubbock, TX to examine the feasibility of partitioning evapotranspiration (ET) from a cotton crop (*Gossypium hirsutum* L.) during periods of partial cover. The Bowen ratio energy balance method and heat balance stem flow measurements were used to make near-instantaneous measurements of ET and T, respectively. Transpiration on a unit land area basis was determined by normalizing stem flow measurements by leaf area or plant density. Soil water evaporation was computed as the difference between ET and T. The accuracy of the method was evaluated by comparing calculated values of E with measured values obtained from soil microlysimeters. Measurements over an 8-day period following an irrigation indicated that daily values of calculated E were within 0.5 mm of measured values in six out of seven comparisons when stem flow measurements were normalized on a leaf area basis. On average, daily calculated E was within $\pm 11\%$ of measured values. Calculated and measured cumulative E agreed to within 0.6 mm at the end of the evaluation period. Computing T by normalizing stem flow on a plant density basis resulted in overestimates of T and underestimates of E. Error analysis indicates that the precision of the E estimate decreases rapidly as evaporation becomes a smaller fraction of ET, and is influenced equally by the resolution of the stem flow and leaf area measurements. This study demonstrates that high frequency, independent measurements of soil and canopy evaporation can be obtained by measurement of ET and stem flow.

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INTRODUCTION

The ability to independently measure soil water evaporation (E) and canopy transpiration (T) is important when examining energy and water balances of sparse vegetation. However, lack of an adequate measurement technique has limited scientists to measurements of evapotranspiration (ET) and/or daily E. Early attempts to obtain separate measures of E and T consisted of using surface-applied barriers to prevent E, and comparing ET from these plots with those without the barriers (Shaw, 1959; Fritschen and Shaw, 1961; Griffin et al., 1966). However, these barriers consisted of materials which modified the surface energy balance and soil moisture conditions. Al-Khafaf et al. (1978) estimated E below a canopy by measuring fluctuations in soil water content and mass changes in sealed embedded containers filled with disturbed soil. Their approach assumed the behavior of the disturbed container was representative of the intact soil, and it was limited to measurements at 3-day intervals.

Development of the microlysimeter (Boast and Robertson, 1982) allowed researchers to make gravimetric measurements of daily E under a crop canopy without drastically modifying the field or soil environment (Shawcroft and Gardner, 1983; Walker, 1984; Lascano et al., 1987). Although the validity of the microlysimeter method has been examined (Walker, 1983; Reynolds and Walker, 1984), daily E data does not provide adequate information for the study of soil–canopy interactions since the timescale of the measurement is different than the dynamics of the transport processes (Walker, 1984). Additionally, near instantaneous measures of E and T are needed for model development and verification (Lascano et al., 1987).

Sakuratani (1987) was the first to report field data on the diurnal patterns of E and T. The Bowen ratio energy balance method was used to measure ET while independent estimates of T were obtained from stem flow measurements. Soil evaporation was computed as the difference between ET and T. Using this technique, he was able to partition ET from a well-watered soybean (*Glycine max* L.) field over 30-min intervals. Sakuratani estimated T per unit land area by measuring stem flow on four plants using the heat balance method (Sakuratani, 1981), then multiplying the average stem flow by plant density. He found that the standard error of the T estimate ranged from 3 to 9% of the mean, and concluded that T could be accurately estimated by measuring flow on a small number of plants. Although Sakuratani's work demonstrated the utility of partitioning evaporative flux by separate measurement of ET and T, no attempt was made to verify the accuracy of the method, or examine errors associated with the technique.

The purpose of our study was to test the accuracy of partitioning ET using the approach introduced by Sakuratani (1987) by comparing calculated values of E with independent measurements of soil evaporation. Additionally, two different approaches for computing T from the stem flow measurements were explored, and their effect on the accuracy examined. A sufficient number of ET and stem flow measurements were made to evaluate the precision of the technique over a range of environmental conditions and to investigate the variability contributed by each component. The results and analysis should assist in future experimental designs and reveal limitations in the approach.

MATERIALS AND METHODS

Experimental site

Experiments were conducted on a 50×50 m plot located at the Texas Agricultural Experiment Station near Lubbock, Texas (33.6°N, 101.8°W). The soil at the site is classified in the Olton series (Fine, mixed, thermic Aridic Paleustoll) with a sandy clay loam surface texture. Other physical properties of the soil are described by Lascano and Van Bavel (1986). Cotton (*Gossypium hirsutum* L. var. Paymaster 404) was planted on 16 May 1989 with ~180 000 plants ha^{-1}. The crop was planted on flat beds with a 1-m row width and north–south row orientation. Other irrigated cotton fields bordered the south and north edge of the plot.

Evapotranspiration/energy balance measurements

Evapotranspiration was determined by measuring the surface energy balance of the field with the Bowen ratio method (Tanner, 1960) using four independent measurement systems designed by Gay and Greenberg (1985). Each system consisted of two exchanging wet and dry bulb psychrometers, a net radiometer, and three soil heat flux plates. The lowest psychrometer on each Bowen ratio mast was 0.75–1.0 m above the soil surface, 0.2–0.45 m above the canopy. Wet and dry bulb temperatures were determined from multiple measurements over a 3-min period, followed by a 3-min interval in which the psychrometers exchanged a vertical distance of 1 m and equilibrated with the environment. This measurement sequence removed the effect of instrument bias, and allowed the determination of the surface energy balance every 12 min. Bowen ratio masts were positioned 8 m from the north edge of the plot to maximize fetch when prevailing southerly winds were present (Fig. 1). The minimum fetch:height ratio during the experiment was 21:1, an adequate value for Bowen ratio measurements (Heilman et al., 1989). Net radiometers (model Q3, Micromet Systems Inc., Seattle, WA) were mounted 2 m above the soil surface with sensors on systems 1 and 3 positioned directly above the plants, and sensors on systems 2 and 4 positioned above the exposed soil, between plant rows. Soil heat flux was determined with the combination approach (Kimball and Jackson, 1979). Flux plates (model HFT-1,

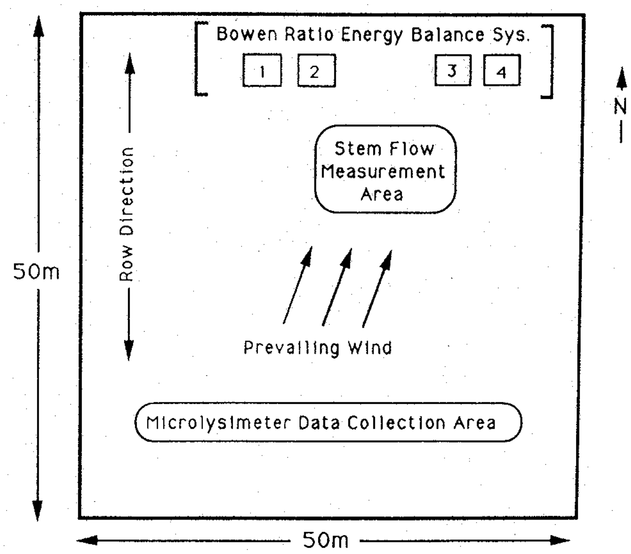

Fig. 1. Diagram of the field plot showing the location of the Bowen ratio energy balance systems, stem flow measurement area, and the microlysimeter data collection area.

Micromet Systems Inc.) were positioned 5 cm below the soil surface and change in storage determined by measuring soil temperature fluctuations in the 0–5 cm layer using three thermocouple probes per system, and an estimate of the heat capacity. The three heat flux plates and corresponding temperature probes associated with each system were spaced 25 cm apart in an east–west line between the rows to measure the spatial average of soil heat flux. Net radiation and soil heat flux measurements for systems 1 and 2 were averaged before calculating the energy balance. The same computational approach was used for systems 3 and 4. All Bowen ratio sensor voltages were sampled and stored using a battery powered data acquisition system (model 71B/3421A, Hewlett Packard, Palo Alto, CA) and results were later transferred to a microcomputer for processing.

Transpiration and soil evaporation measurements

Stem flow was measured on 8–9 plants upwind of the Bowen ratio systems (Fig. 1) using the heat balance approach (Sakuratani, 1981). Continuous stem flow measurements were made for 3–4 days, and then plants were harvested and the leaf area measured using a digital area meter (Delta-T Devices Ltd., Cambridge, U.K.). Plant density was measured by counting the number of plants along a 1 m transect bisecting the location of each plant. Stem flow gauges were constructed according to the design described by Baker and Van Bavel (1987) using the wiring configuration of Steinberg and Van Bavel (1990). Approximately 0.15 W of power was applied to the stem via a thin resistance heater 12 mm wide, in accordance with the recommendations of Ham and Heilman (1990). Axial temperature gradients were measured with two pairs of thermocouple sensors positioned above and below the heater, separated by a distance of 5 mm. Radial heat flow was measured using a 10-junction thermopile. The entire gauge was encapsulated in foam insulation approximately 13 mm thick and 60 mm in length. Gauge signals were sampled every 15 s using a datalogger-multiplexer unit (model 21X/AM32, Campbell Scientific Inc., Logan, Utah), and 12-min averages computed for storage. Laboratory tests with cotton and sunflower (*Helianthus annuus* L.) indicate the heat balance method can determine transpiration within 5–10% (Baker and Van Bavel, 1987; Ham and Heilman, 1990). Rigorous discussions of the heat balance stem flow measurement technique are given by Baker and Van Bavel (1987), and Ham and Heilman (1990).

Stem flow measurements from the individual plants were converted to a vapor flux per unit land area using two approaches. First, mean transpiration, T_l, in kg m^{-2} s^{-1}, was determined from flow measurements on n plants by normalizing the stem flow data on a leaf area basis using the equation

$$T_l = \Sigma(f_i/\chi_i)/n \times LAI \qquad (i=1,2,....,n) \tag{1}$$

where f_i is measured stem flow, kg s^{-1}, χ_i is the leaf area, m^2, of plant i, and LAI is the leaf area index of the plot. In the second approach, mean transpiration, T_d, was computed by normalizing the stem flow data on a population basis as

$$T_d = \Sigma(f_i \rho_i)/n \quad (i=1,2,...,n) \tag{2}$$

where ρ_i is the plant density, plants m^{-2}, associated with gauge–plant combination i. Equation 2 assumes that individual plants used for stem flow measurement are representative of the entire population, while eqn. 1 normalizes the flow from each plant by the ratio of its leaf area to that of the entire canopy, as given by the LAI. Both of these approaches assume that hydraulic capacitance in small herbaceous plants is minimal and stem flow measurements provide a good estimate of T (Ham and Heilman, 1990).

Soil evaporation was calculated as the difference between ET and T, and also measured with soil microlysimeters. Calculated soil water evaporation, E_c, in kg m^{-2} s^{-1}, was computed as

$$E_c = ET - T \tag{3}$$

where ET and T were measured with the Bowen ratio system and stem flow gauges, respectively. Results from all four Bowen ratio systems were averaged to provide an estimate of ET from the entire plot. Soil evaporation was determined at 12-min intervals throughout the day. Daily estimates of ET, T and E were computed by integrating the respective measurements over daylight periods. Calculated soil evaporation as determined using the leaf area and plant density-based measures of T will be referred to as $E_{c,l}$ and $E_{c,d}$, respectively.

Direct microlysimeter measurements of daily soil water evaporation, E_m, were made following the procedures described by Lascano and Van Bavel (1986). Microlysimeters, 0.13 m long and 0.074 m in diameter, were installed midway between the rows, approximately 5–15 m from the south edge of the plot (Fig. 1). The instruments were installed before dawn each day, and then removed and weighed after sunset. Results from 20 to 30 microlysimeters were averaged to compute daily soil water evaporation.

Additional measurements

Leaf area index was measured every 5–7 days throughout the growing season by sampling 10 random plants and multiplying the measured leaf area for each plant by the plant density at the harvest location. Estimates of LAI for periods between measurement days were obtained by fitting a curve to the measured values ($R^2=0.97$). Other phenological measurements such as canopy height and width were made on a weekly basis. Soil volumetric water content was determined gravimetrically every 1–2 days from volumetric samples of the 0–4 cm soil layer. Additional environmental measurements included wind speed at 1.5 m, wind direction, and global irradiance.

RESULTS AND DISCUSSION

Measurements were made during an 8-day period from 8 August (calendar Day, CD 220) to 15 August (CD 227) 1989. The evaluation period was preceded by a 40 mm irrigation on CD 218, and the drying cycle was disrupted on CD 225 by rain (19 mm). Environmental, soil, and canopy conditions during the evaluation period are given in Table 1. Canopy height and width were approximately 0.51 and 0.54 m, respectively.

Partitioning evapotranspiration

Daily totals of all evaporative components over the evaluation period are given in Table 2. Bowen ratio measurements of ET ranged from 4.3 to 7.9 mm day^{-1} and transpiration measurements based on leaf area, T_l, (eqn. 1) ranged between 3.0 and 4.2 mm day^{-1}. Calculated values of soil evaporation, $E_{c,l}$, (eqn. 3) were within 0.5 mm of the microlysimeter measurements, E_m, on 6 out of 7 days (Fig. 2). Differences between $E_{c,l}$ and E_m ranged from -21 to $+22\%$ (Table 2). However, on average, calculated and measured values of daily E agreed to within $\pm 11\%$. The largest difference between $E_{c,l}$ and E_m occurred on CD 221 when the microlysimeter measurement was 1.1 mm greater than $E_{c,l}$. However, the same relationship was not observed on days

TABLE 1

Observed daytime values of maximum and minimum air, T_{air}, and dewpoint, T_{dew}, temperatures, average wind speed, u, and total global irradiance, Rs, as measured during the evaluation period. Also included are volumetric soil water content, θ, from 0 to 4 cm, and leaf area index, LAI

Day	T_{air} (°C) Max	T_{air} (°C) Min	T_{dew} (°C) Max	T_{dew} (°C) Min	u ($m\ s^{-1}$)	Rs ($MJ\ m^{-2}\ day^{-1}$)	θ ($m^3\ m^{-3}$)	LAI ($m^2\ m^{-2}$)
220	24.6	15.1	15.7	14.3	1.3	25.9	0.32	2.09
221	26.1	13.5	15.0	10.4	3.2	26.3	0.29	2.17
222	28.4	16.4	17.2	13.1	3.7	24.1	0.29	2.26
223	26.5	17.8	17.8	13.8	3.5	25.5	[a]	2.35
224	26.5	18.5	18.4	14.7	2.5	16.1	0.21	2.45
225	←				Rain			→
226	25.8	17.4	19.6	16.2	2.4	24.7	[a]	2.64
227	29.0	16.3	18.5	15.7	1.4	25.1	0.27	2.74

[a]Not measured.

TABLE 2

Daily evapotranspiration, ET, transpiration, T, and soil evaporation, E, in mm day^{-1}. Transpiration, T_l and T_d were obtained from stem flow data normalized by leaf area and plant density, respectively. Calculated soil evaporation, $E_{c,l}$ and $E_{c,d}$, is the difference between ET and T_l or T_d. Also included are independent microlysimeter measurements of E, E_m, and the ratios of calculated and measured E, E_c/E_m

Day	ET	Transpiration T_l	Transpiration T_d	Soil evaporation $E_{c,l}$	Soil evaporation $E_{c,d}$	Soil evaporation E_m	$E_c:E_m$ ratio $E_{c,l}/E_m$	$E_c:E_m$ ratio $E_{c,d}/E_m$
220	6.1	3.0	5.5	3.1	0.6	3.2	0.97	0.18
221	7.7	3.6	6.3	4.1	1.4	5.2	0.79	0.27
222	7.8	4.0	7.5	3.9	0.3	3.5	1.11	0.09
223	7.5	4.2	7.4	3.3	0.1	2.7	1.22	0.03
224	4.3	3.2	4.9	1.1	−0.6	1.2	0.92	−0.50
225	←			Rain				→
226	6.0	3.9	5.5	2.1	0.5	2.4	0.88	0.21
227	6.2	4.0	5.5	2.2	0.7	2.2	1.00	0.32
Total[a]	45.7	25.9	42.6	19.8	3.1	20.4		

[a]Evaporation on Day 225 was not included.

with similar environmental and soil moisture conditions (CD 220 and 222). A plot of cumulative calculated and measured E over the test period showed no evidence of systematic errors (Fig. 3), and evaporative totals agreed to within 0.6 mm at the end of the measurement period (Table 2). Since $E_{c,l}$ was computed as a residual, measurements of ET and T must have been reasonably accurate to produce the agreement in $E_{c,l}$ and E_m observed in Figs. 2

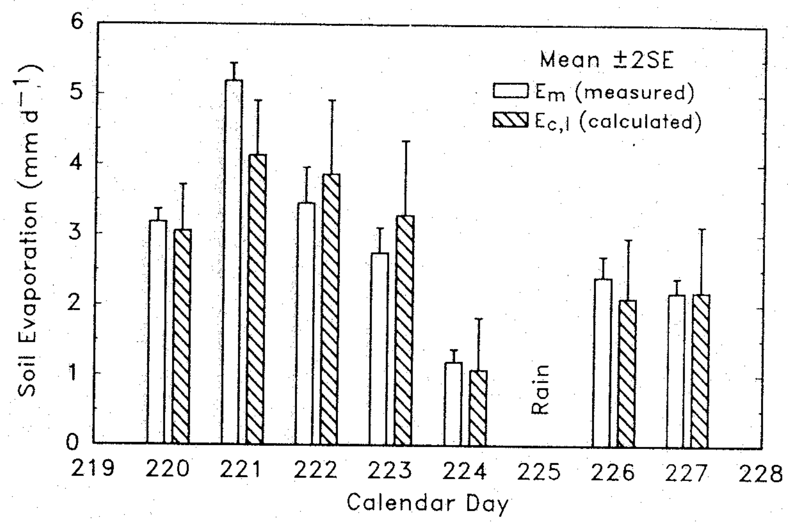

Fig. 2. Daily calculated soil evaporation, $E_{c,l}$, determined as the difference between Bowen ratio measurements of evapotranspiration and stem flow estimates of transpiration. Results are compared with independent measurements of soil evaporation, E_m, obtained from microlysimeters.

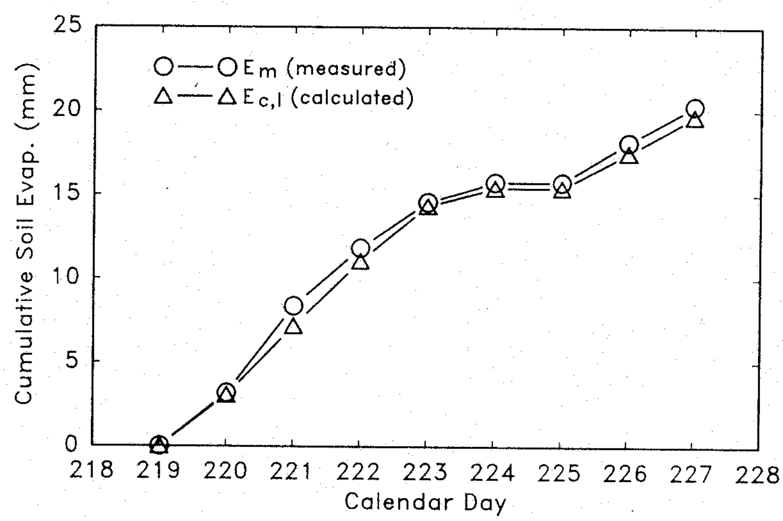

Fig. 3. Comparison of measured, E_m, and calculated, $E_{c,l}$, cumulative soil water evaporation over the test period. For presentation purposes, evaporation on Day 225 was assumed to be negligible due to rain.

and 3. These results substantiate the feasibility of partitioning *ET* by energy balance and stem flow measurement, and tend to validate all techniques used to make the comparison.

The importance of determining *T* from stem flow measurements weighted by leaf area is demonstrated in Table 3. Results from CD 226 illustrate the high correlation ($r=0.82$) between leaf area and stem flow for nine gauge-

TABLE 3

Results from the stem flow normalization procedure on Day 226, showing the leaf area for each individual plant and stem flow on a mass per unit plant, and mass per unit leaf area basis

Gauge–plant	Leaf area (m^2 per plant)	Stem flow	
		Measured (kg per plant day^{-1})	Normalized (kg m^{-2} day^{-1})
1	0.243	0.451	1.86
2	0.181	0.312	1.72
3	0.403	0.742	1.84
4	0.290	0.325	1.12
5	0.227	0.243	1.07
6	0.265	0.323	1.22
7	0.251	0.440	1.75
8	0.237	0.267	1.12
9	0.240	0.387	1.61
Mean	0.260	0.388	1.48
SE	0.02	0.05	0.11
SE/mean	7.8%	13.0%	7.7%

plant combinations. The standard error for the raw flow measurements was 13% of the mean, and the variation in stem flow per unit leaf area was 7.7% of the mean. Thus, variation among plants was reduced by almost half when stem flow was normalized on a leaf area basis. The normalization process on other days during the test period produced similar results.

Transpiration measurements based on population, T_d, (eqn. 2) were, on average, 63% larger than those normalized by leaf area, which resulted in calculated soil evaporation, $E_{c,d}$, values much lower than E_m (Table 2). These results agree with the work of Dugas (1990) who found that unadjusted stem flow measurements overestimated transpiration from cotton planted on a lysimeter. Plant size within our canopy was variable, and included many plants that were much smaller than those used for stem flow measurement. As a result, T was overestimated since stem flow within these small plants was much less than that measured with the gauges. Converting stem flow measurements to a unit land area basis by simply multiplying by plant density does not appear feasible when high plant-to-plant variability exists. The inadequacy of this approach would be more prevalent in crops which are planted without precise control of plant spacing.

Diurnal patterns of evaporation

Although good evidence exists that evapotranspiration can be partitioned on a daily basis using separate measurements of ET and stem flow, the prin-

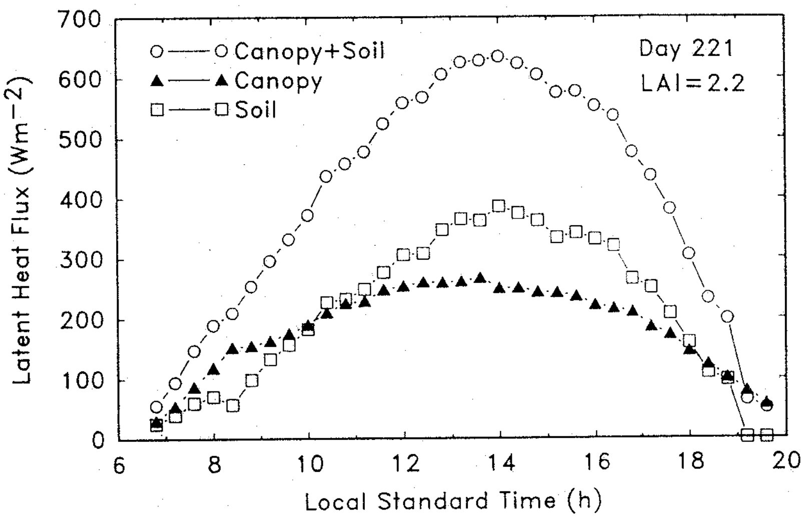

Fig. 4. Diurnal pattern of latent heat flux from the soil and canopy on Day 221, 2 days following an irrigation. The volumetric soil surface water content was 0.29. and the *LAI* of the cotton canopy was 2.2. Skies were clear.

ciple value of the method lies in the ability to measure the detailed patterns of E and T throughout the day. As an example, latent heat flux from the canopy and soil on CD 221 is presented in Fig. 4. Latent heat flux from the canopy followed the diurnal course of irradiance, as would be expected during clear skies. Energy consumed in E was less than that accounted for by the canopy when the solar elevation angle was small, and the soil was shaded by the canopy. As irradiance at the soil surface increased, E exceeded T, and accounted for over 60% of total latent heat flux near solar noon.

Error analysis

When a final result is computed from direct measurements, its precision is a function of the variability in the direct measurements (Barry, 1978). This theory can be applied to the computation of T and E when using the "Bowen ratio–stem flow" approach to partition ET. The precision of the T estimate is determined from variation in stem flow and LAI, and the precision of the E estimate also includes variation in ET.

Soil water evaporation can be computed by rewriting eqn. 3 as follows

$$E_{c,1}=ET-F\times LAI, \quad (4)$$

where F is mean stem flow per unit leaf area in kg m^{-2} s^{-1}. Since ET, F, and LAI are all mean values, the precision of each parameter is available in terms of its standard error. Applying the procedures of Barry (1978), the standard error of $E_{c,1}$ can be determined as

$$\sigma_E = [\sigma_{ET}^2 + (\sigma_{LAI} F)^2 + (\sigma_F LAI)^2]^{1/2} \tag{5}$$

where σ_{ET}, σ_{LAI}, and σ_F are the standard errors for ET, LAI, and F, respectively. This formula assumes that variability in ET, F, and LAI is normally distributed and independent. Although independence cannot be assured, it is still reasonable to pursue the analysis since all three parameters are the result of separate measurement systems. The standard error for the T estimate can be determined by omitting σ_{ET} from eqn. 5.

Equation 5 shows that σ_E is influenced by the magnitude of F and LAI, or collectively, T. Since all terms are linked by the mass balance equation, it is possible to rewrite eqn. 5 in terms of the fraction of ET originating from the soil

$$\frac{\sigma_E}{E} = \left\{ \left(\frac{E}{ET}\right)^{-2} \left(\frac{\sigma_{ET}}{ET}\right)^2 + \left[\left(\frac{E}{ET}\right)^{-1} - 1\right]^2 \left[\left(\frac{\sigma_{LAI}}{LAI}\right)^2 + \left(\frac{\sigma_F}{F}\right)^2\right] \right\}^{1/2} \tag{6}$$

and express the variability of all parameters relative to their respective mean. This analysis indicates that the precision of E is more heavily influenced by variation in F and LAI when E/ET is small. However, as E/ET approaches unity, the term containing F and LAI becomes less significant, and the variability in E is dominated by the measurement of ET.

During the evaluation period, the standard errors of F and ET with respect to their means were similar, having values of approximately 0.1. Thus, variation in F and LAI typically had equal influence on the precision of the E estimate. The standard error for ET, determined from the results of the four Bowen ratio systems was approximately 0.005. The behavior of eqn. 6, when using these typical variance levels, is demonstrated in Fig. 5. The expected variation in $E_{c,1}$ increases rapidly as E becomes a smaller component of the evaporative total. This nonlinear response is the result of F and LAI having greater influence as E/ET is reduced. The rapid decline in the precision of the E estimate at low soil evaporation levels indicates the utility of the approach may be limited when E is less than 20% of total ET. This restriction may hinder quantification of surface energy balance relationships and transport processes during certain soil and canopy conditions. However, it is important to note that eqn. 6 represents variation relative to the mean, and is not an indication of accuracy. Adequate resolution still exists for most water and energy balance studies since precision is high when E is most significant. During our study, measured values of σ_E ranged from 9 to 34% of the mean, having an average value of 18%. This result is consistent with Fig. 5 given that E/ET was approximately 0.43 over the test period.

For the purpose of comparison, eqn. 6 was reanalyzed after reducing the relative standard error for F to 0.01 (Fig. 5). This alteration had little effect

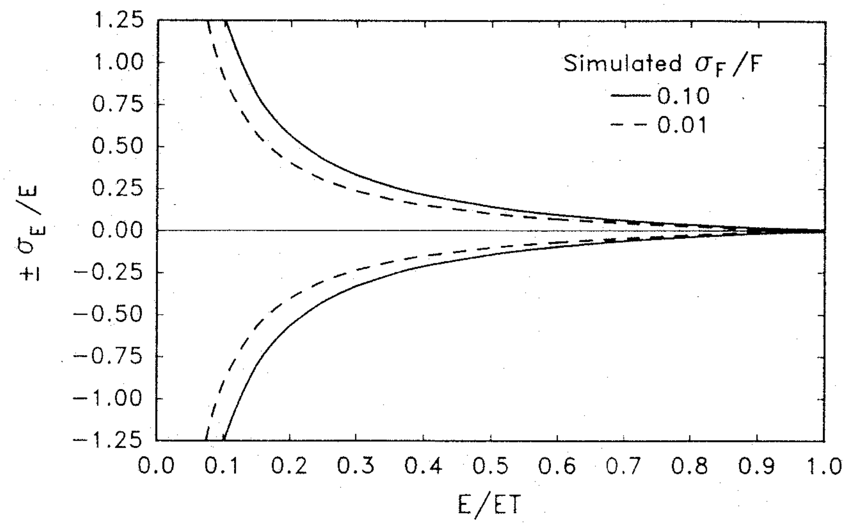

Fig. 5. Expected variation, σ_E/E, for the soil evaporation estimate in response to the fraction of evaporation originating from the soil surface, E/ET (eqn. 6). The family of curves show the response for two simulated levels of variation in F, the mean stem flow on a mass per unit leaf area basis. Relative variation in ET and LAI (σ_{ET}/ET and σ_{LAI}/LAI), was held constant at 0.005 and 0.1, respectively.

on the precision of E since the standard error of the LAI measurement remained sufficiently high to produce the observed response. These results suggest that increasing the precision of the stem flow measurement (i.e. increasing the number of stem flow measurements) will not greatly enhance the precision of $E_{c,l}$ unless the precision of the LAI measurement is improved simultaneously. Given the state of available instrumentation, it is probable that the resolution of $E_{c,l}$ and T_l may be restricted by the precision of the LAI determination.

The error response for $E_{c,l}$ as a function of E/ET (Fig. 5) assumes the variation of the direct measurements is constant. However, diurnal variation in the direct measurements also influences the resolution of the E estimate over the day. In our study, variation in ET and F was greatest during the early morning and late afternoon when the solar elevation angle was small (Fig. 6). This response may have been caused by shading effects within the canopy and differences in stomatal behavior among plants. Thus, predicted variation in $E_{c,l}$ was compounded by changes in E/ET and diurnal differences in variation among the direct measurements. In general, the resolution of the technique will be the greatest when the standard error of the stem flow measurements is small, and E/ET approaches its daily maximum.

Measured variation in stem flow (i.e. transpiration) among plants is not only needed for error analysis, but also represents another source of useful information. These data may help characterize factors affecting plant-to-plant

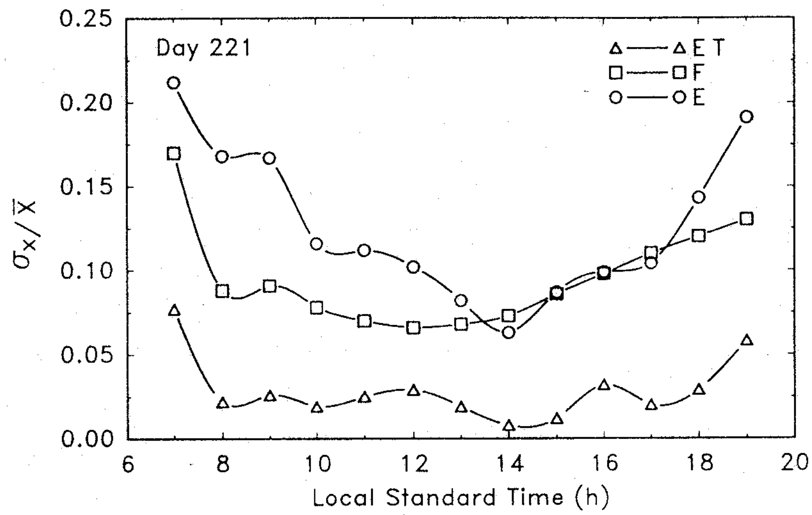

Fig. 6. Diurnal variation in ET, F and E as measured on Day 221 during the evaluation period. Standard errors in ET and F were computed directly from the Bowen ratio and stem flow measurements, respectively. The standard error for soil evaporation, E, was computed from eqn. 6.

variability within a canopy, and quantify parameters needed for stochastic modeling approaches.

As with any measurement technique, the "Bowen ratio–stem flow" approach has several inherent limitations which should be mentioned. Evaporation measurements will be less accurate at night when stability conditions in the equilibrium sublayer hinder Bowen ratio measurements of ET. Additionally, heat balance stem flow measurements have only been verified on small herbaceous dicot stems and small trees. Therefore, further research is needed to apply the approach to other plant types. The technique is limited to uniform cropping systems where stem flow measurements on several plants can be used to represent the entire vegetal surface. However, techniques may be developed for determining T from heterogenous vegetation. Evaporation of dew from the canopy foliage could also lead to errors. Bowen ratio measurements detect all sources of water vapor, and dew evaporation will increase measured ET and result in a large E value (Sakuratani, 1987). Since the origin of the dew could be from the soil or air (Monteith, 1957), the meaning of the computed E value during this process is unclear. Thus, early morning measurements need to be scrutinized when dew formation is common.

CONCLUSIONS

Results indicate that partitioning ET into soil and canopy components by measurement of ET and stem flow is viable, provided that T is determined by normalizing stem flow on a leaf area basis. Attempts to compute T by normalizing stem flow on a plant density basis proved inadequate. However, further experimentation is required to determine the effect of canopy variability on the feasibility of each approach.

Error analysis indicates that the resolution of the T estimate is equally dependent on the precision of the stem flow and LAI measurement. The relative precision of the residual E estimate decreases rapidly as E becomes a smaller portion of ET. These results suggest that precise measures of E may not be feasible when the soil surface is dry and a well developed canopy is present.

The ability to measure the diurnal pattern of E and T should greatly improve our understanding of surface energy balance relationships and within canopy transport in sparse vegetation. Data of this type are not currently available, yet they are an indispensable requirement for model development and verification.

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